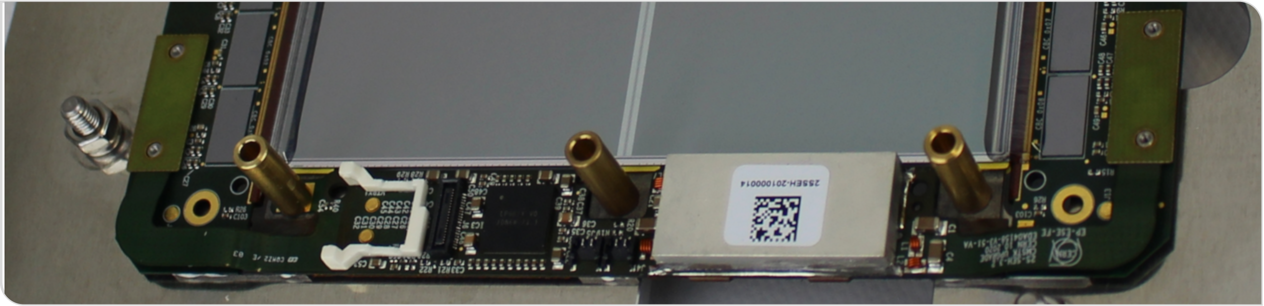
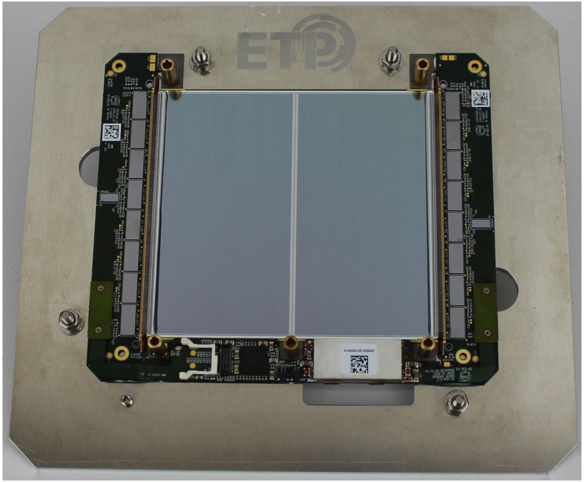
Functional Tests of Silicon Strip Sensor Modules for the CMS Experiment

Roland Koppenhöfer | March 14, 2022



Outline

- The High Luminosity LHC & the CMS Experiment
- 2S Module Assembly
- Functional Tests of 2S Modules
- Summary & Outlook

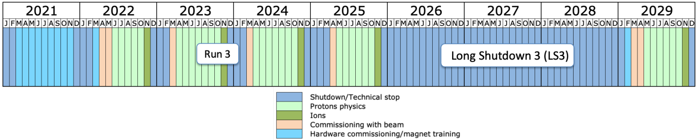


The High Luminosity LHC & the CMS Experiment

High Luminosity LHC

Karlsruhe Institute of Technology

- LHC delivers proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ and 40 MHz bunch crossing rate
- Upgrades to accelerator and detectors necessary during runtime for especially exposed hardware
- **High Luminosity LHC (HL-LHC)**
  - Begin of operation in 2029
  - Increase in instantaneous luminosity (factor 5 to 7)



- Increased integrated luminosity (factor ten after ten years of operation)
  $\Rightarrow$ larger datasets
  $\Rightarrow$ uncertainties on precision measurements of key physics processes (e.g. Higgs coupling) decrease

(Instantaneous) Luminosity $\mathcal{L}$

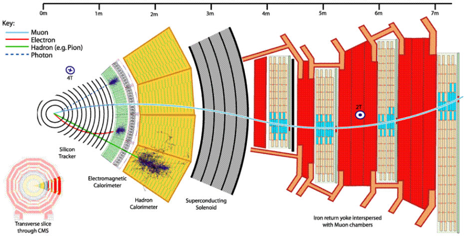
$$\frac{\mathrm{d}N_i}{\mathrm{d}t} = \mathcal{L} \cdot \sigma_i \qquad [\mathcal{L}] = \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

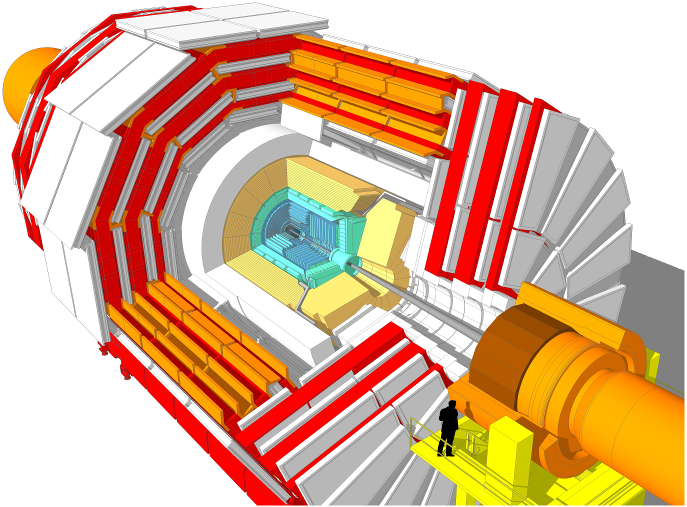
Integrated Luminosity $\mathcal{L}_{\text{int}}$

$$N_i = \sigma_i \cdot \int_0^T \mathcal{L}(t)\,\mathrm{d}t = \sigma_i \cdot \mathcal{L}_{\text{int}} \qquad [\mathcal{L}] = \mathrm{fb}^{-1}$$

The Compact Muon Solenoid (CMS) Experiment

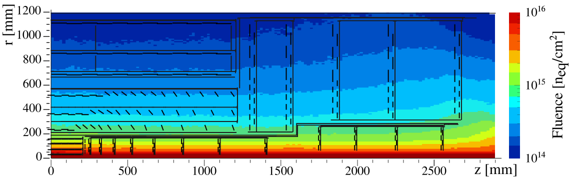
- Subdetectors located cylindrically around beam pipe
  - Silicon tracker
  - Electromagnetic calorimeter
  - Hadronic calorimeter
  - Superconducting solenoid ($B = 3.8\,\mathrm{T}$)
  - Muon chambers
- Particle identification by unique (combined) signature in subdetectors





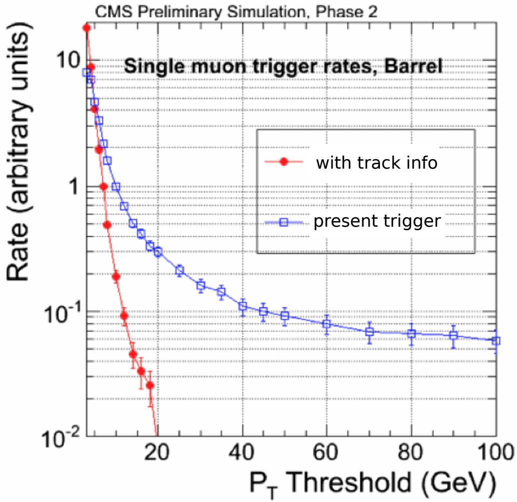
HL-LHC Conditions for the CMS Experiment

- Increased radiation levels



- Simultaneous interactions per bunch crossing up to 200 (currently $\approx$ 30)
  - Increased particle density degrades performance of present trigger system

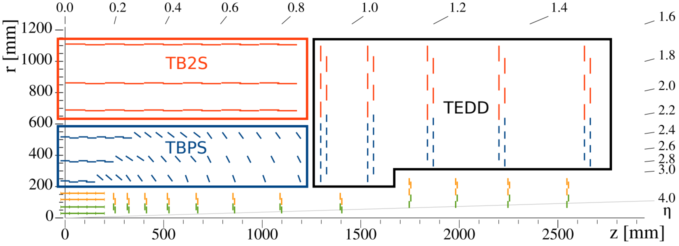
- Solution to keep trigger rates under control: **include track information trigger decision**

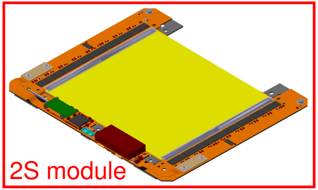


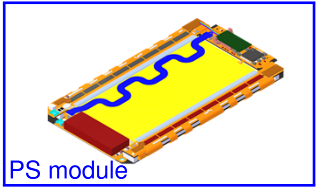
[L. Skinnari 2014 JINST 9 C10035]

Phase-2 Upgrade of the CMS Outer Tracker

- Complete exchange of CMS silicon tracker
- ≈ 13 000 double-sided modules
  - 2S modules: strip/strip sensor
  - PS modules: pixel/strip sensor
- Features of the tracker upgrade:
  - Improved radiation tolerance
  - Increased granularity
    → higher data output
  - Zero suppressed binary readout of hits in channels
  - p_T-modules contribute to first CMS trigger stage at 40 MHz data rate
  - Modules will be operated at sensor temperatures of $\approx -20°C$



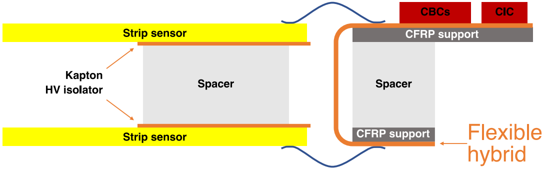


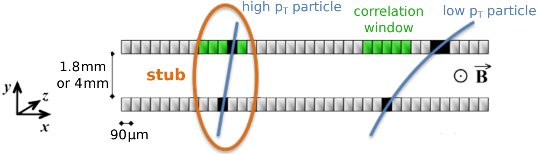


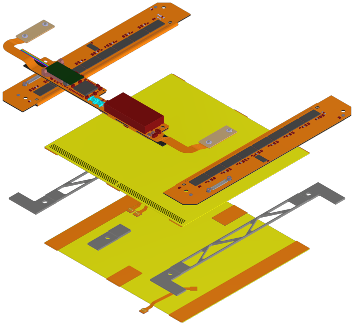
- ETP pledged to build 2000 2S Modules by 2025

p_T-Module Concept

- Identify particles with $p_T > 2\,\mathrm{GeV/c}$ on module level
- Spatial correlation of hits in two sensor layers in magnetic field
- Required: good sensor alignment in module







2S Module for the CMS Outer Tracker

Service Hybrid

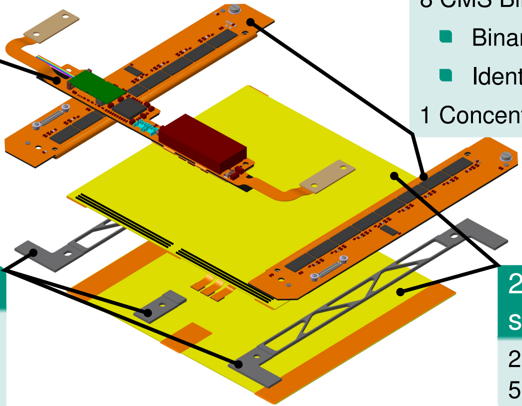
Powering
Data transmission

2 Front-end Hybrids

8 CMS Binary Chips[2] each

- Binary readout of sensor signals
- Identification of stubs

1 Concentrator Chip each



Al-CF[1] Spacer

Spacing between sensors
Main cooling path
Mechanical fixation

2 parallel silicon strip sensors

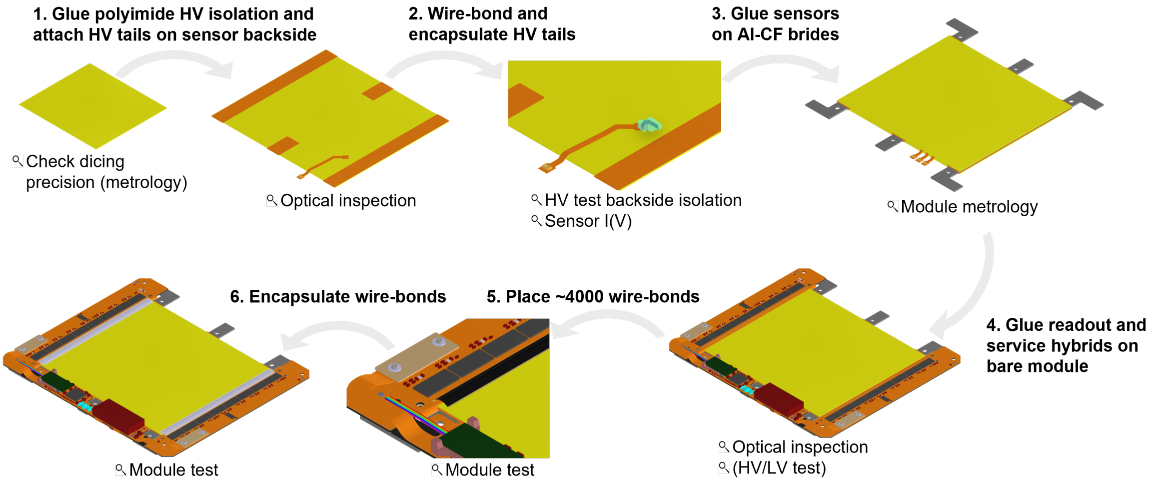
2×1016 strips each
5 cm length, 90 µm pitch

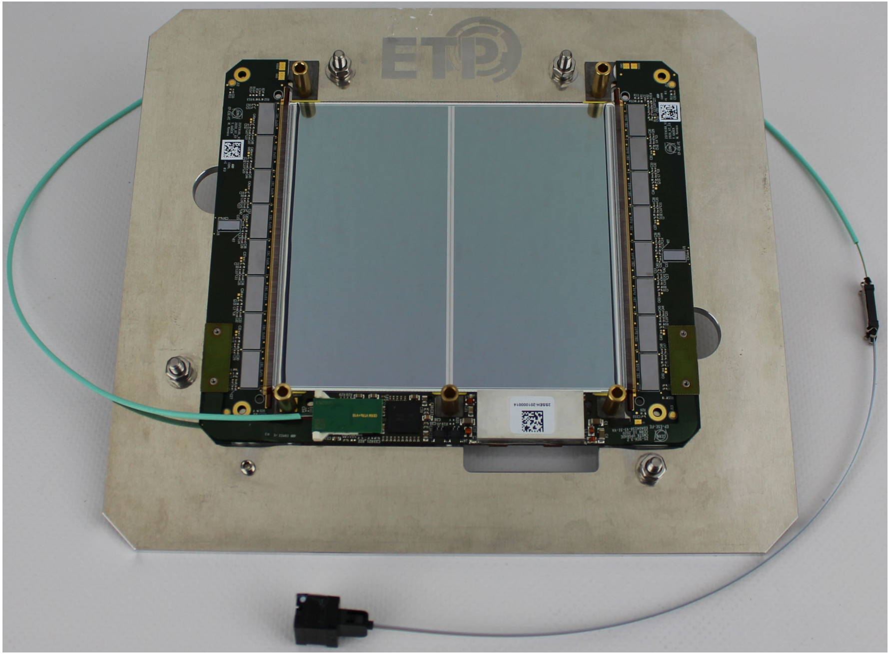
[1] Aluminum / carbon fiber composite

[2] Prydderch et al., *CBC3: a CMS microstrip readout ASIC with logic for track-trigger modules at HL-LHC*, CMS-CR-2017-383

2S Module Assembly

Assembly and Test Procedure of 2S Modules




ETP

Functional Tests of 2S Modules

Overview over Functional Module Testing

- Since 2017: about 50 functional full-size module prototypes built by CMS OT community
  - Available module components were not final versions yet (sensors, readout chips, hybrids, . . .)
  - **Thorough testing of module prototypes necessary** towards final modules!

- Module tests covered in this talk:

  1. (Quick) readout test after assembly
  2. Resilience tests using thermal cycling
  3. Beam tests of modules with unirradiated and irradiated sensors

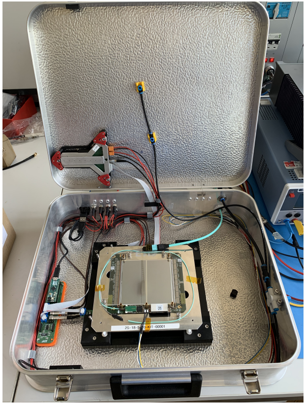
1. Module Readout Test after Assembly

Module Readout Test after Assembly – Test Stand

- Every module will be tested twice at the end of module assembly process
- Development of comparable test hardware for all module assembly centers needed
  $\rightarrow$ dedicated test stand designed at ETP: **The OT module test bench**

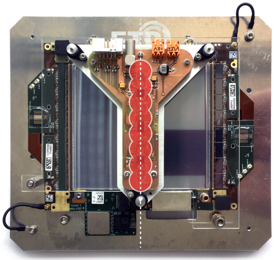
- Test goals:
  - Measure module $I(V)$ characteristic
  - Test module readout chain
  - Spot channel defects
- Test stand features:
  - Quick and safe mounting of modules
  - Karlsruhe Infrared Array (KIRA)
  - Temperature and humidity monitoring
  - Operation safety mechanisms
  - Compatible for 2S and PS module testing

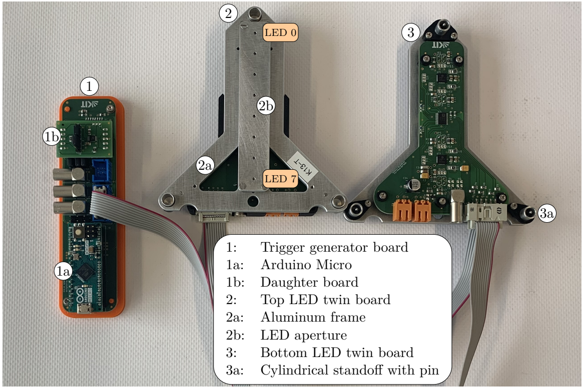
- ETP produced all OT module test benches for the CMS community



Module Readout Test after Assembly – KIRA

- External charge generation in silicon sensors via infrared LEDs
- Eight LEDs illuminate each sensor along its center line
- Features
  - Individually controllable LED brightness
  - Operation with realistic trigger and pulse rates possible ($\approx$ 10 kHz)

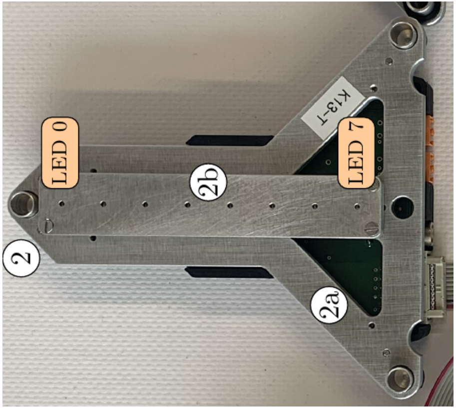


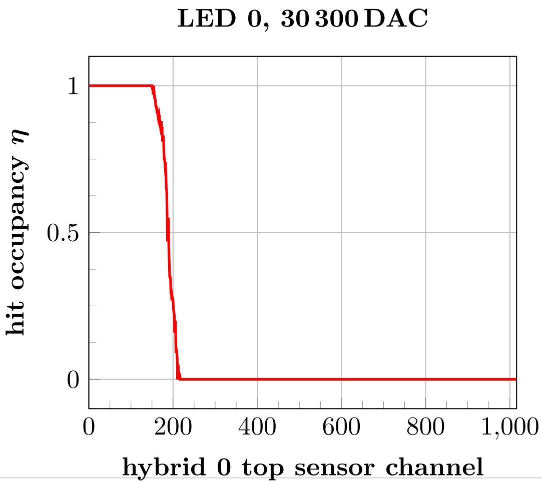


Module Readout Test after Assembly – Test Results

- Full sensor illumination achievable with KIRA system
- Channel defects detectable during KIRA illumination by deviations from $\eta = 1$

$$\eta = \frac{\text{number of hits per channel}}{\text{number of triggered events}}$$





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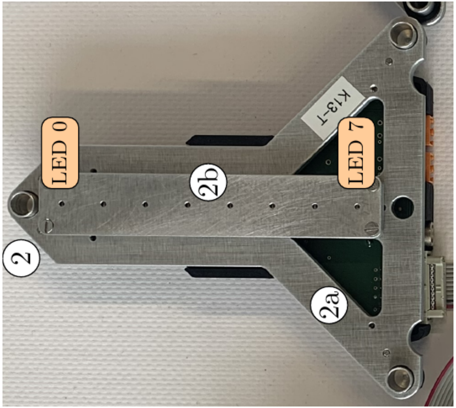

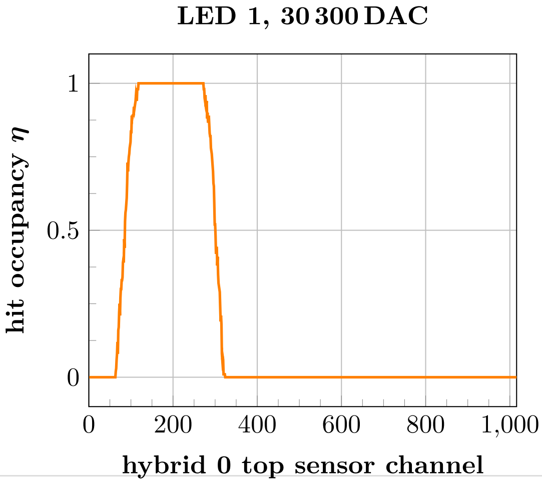

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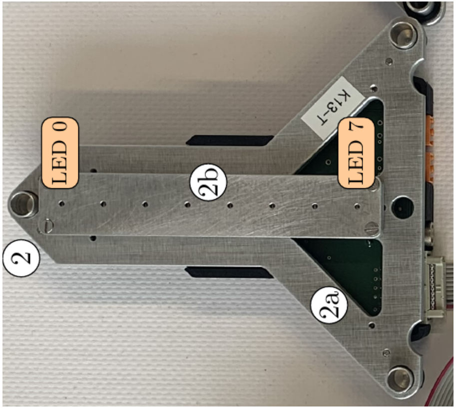

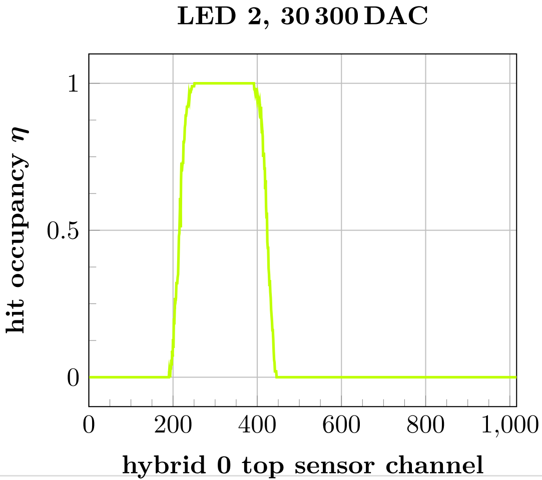

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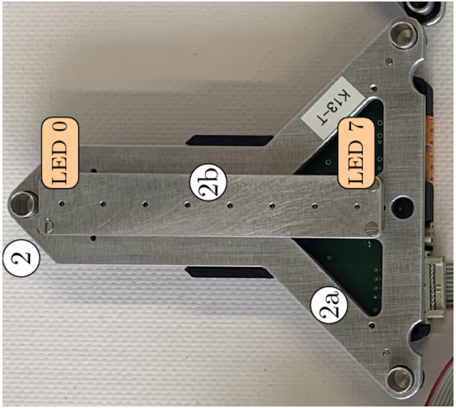

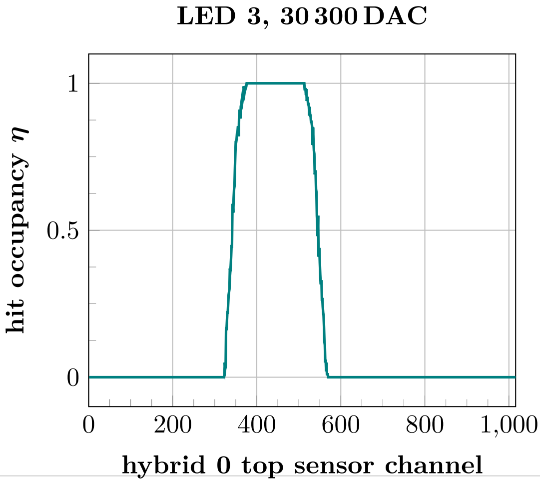

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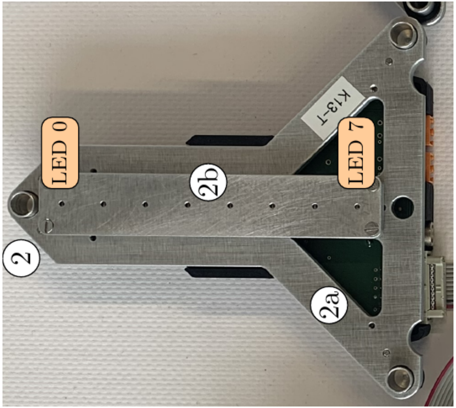

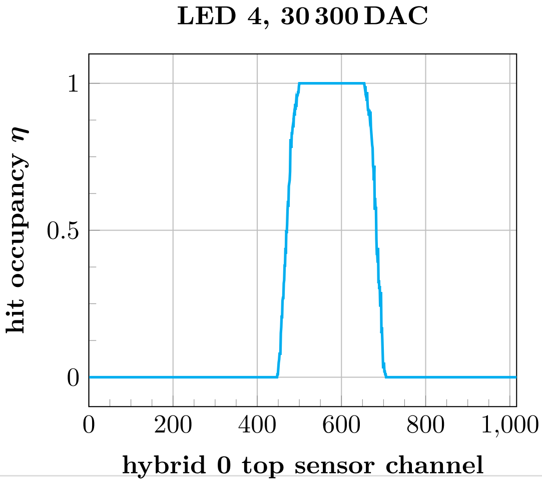

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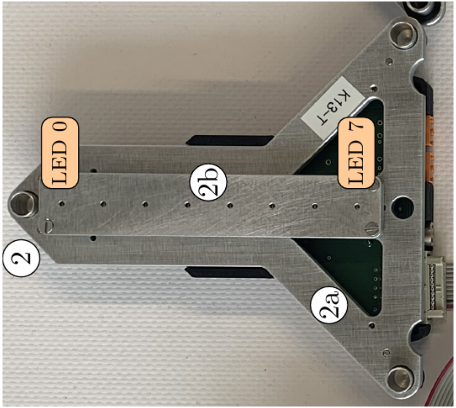
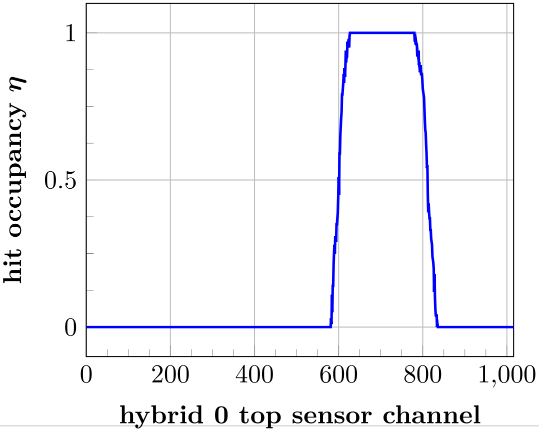


LED 5, 30 300 DAC



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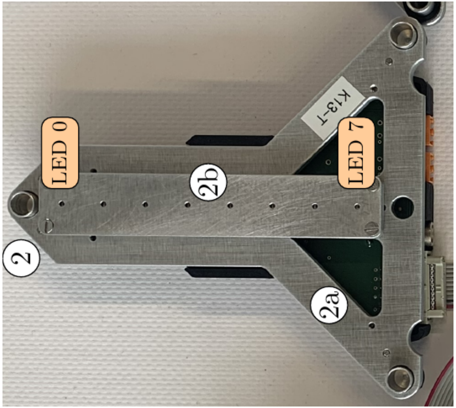

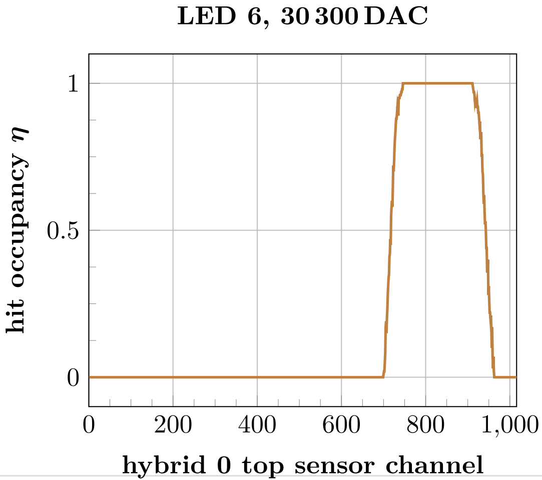

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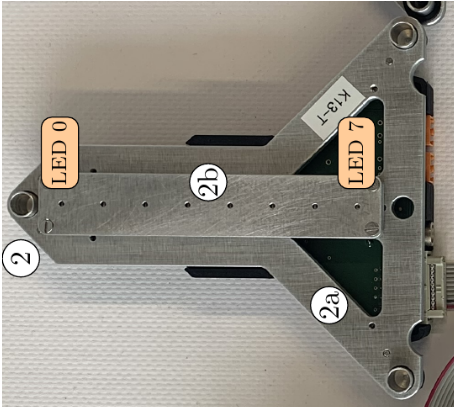

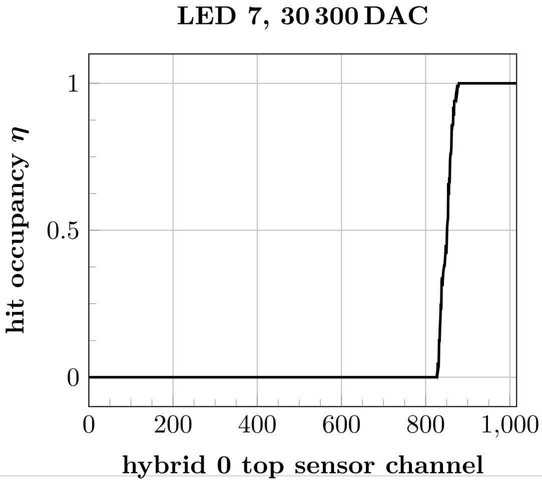

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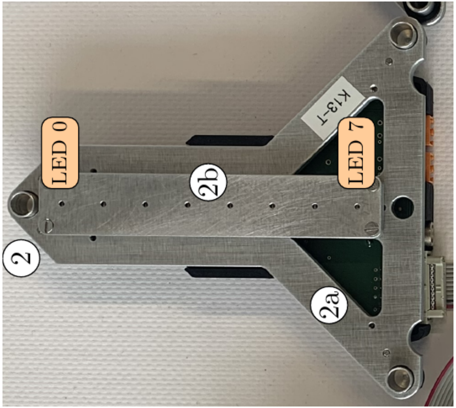
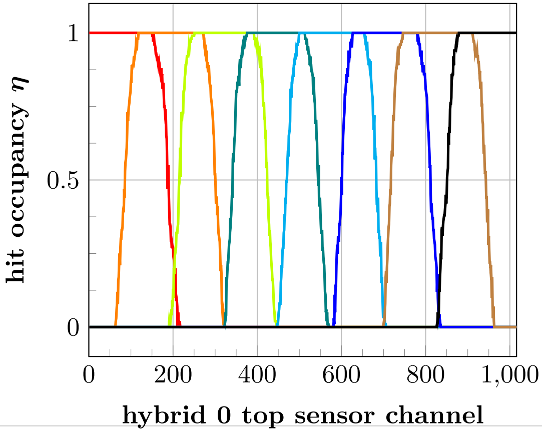
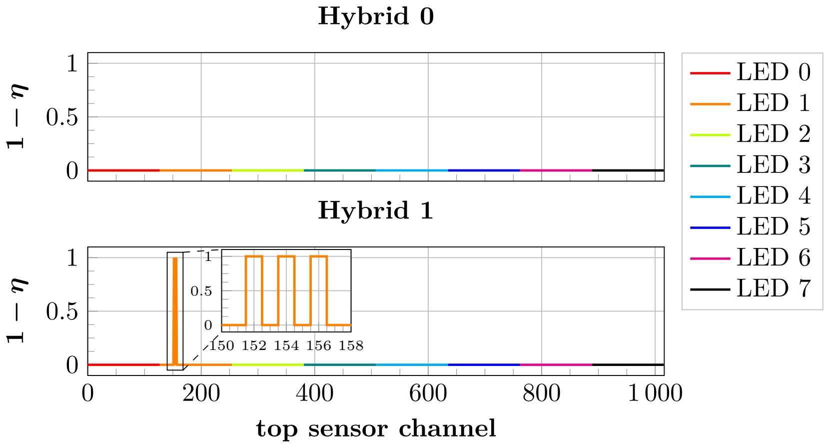


All LEDs, 30 300 DAC



Module Readout Test after Assembly – Test Results

- Combine data from individual LED measurements
- Plot $1 - \eta$ to easily spot deviations from expectation of hit occupancy of one

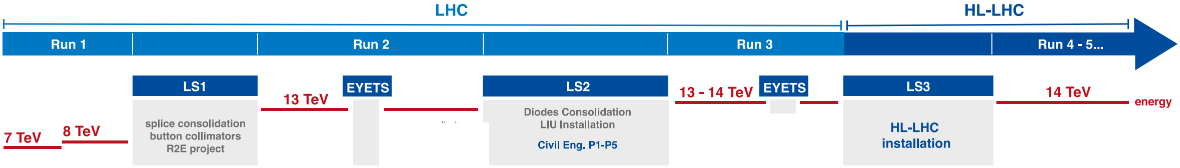


- Three unconnected wire-bonds due to bond pad contamination on frontend hybrid

2. Resilience Tests using Thermal Cycles

Resilience Tests using Thermal Cycling

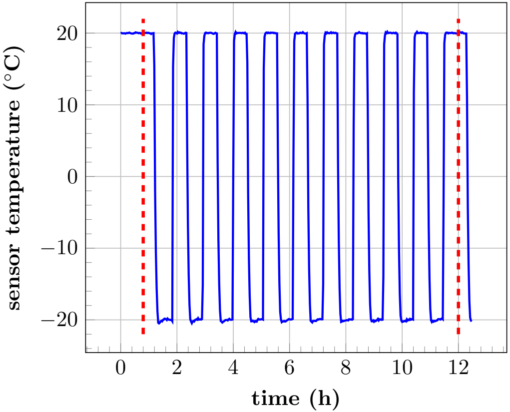
- CMS Tracker will be operated cold ($\vartheta_{\text{sensors}} \approx -20°\text{C}$)
- Warming up of tracker during shutdown times necessary and desired (e.g. service phases, improvement of sensor leakage current, . . .)
  $\Rightarrow$ **Tracker modules have to endure thermal cycles**

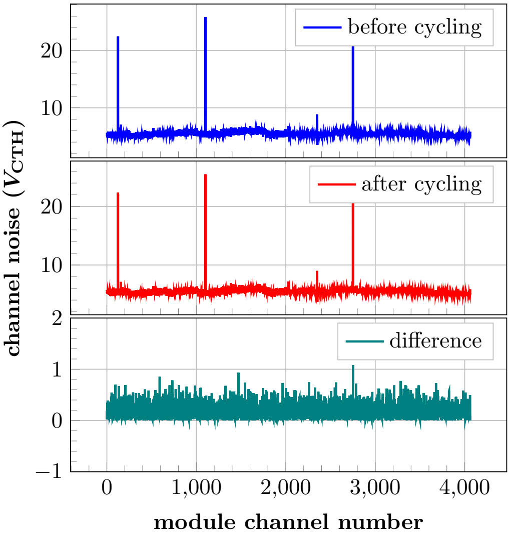


- All modules will be temperature cycled before integrating into the CMS detector
  - Reduce risk of module "infant mortality" after integration into detector

Resilience Tests using Thermal Cycling – Measurements

- Thermal cycles with several prototype modules
- 80 cycles with $-20°C \leq \vartheta_{sensors} \leq 25°C$
- Module functional tests every 10 cycles at $20°C$

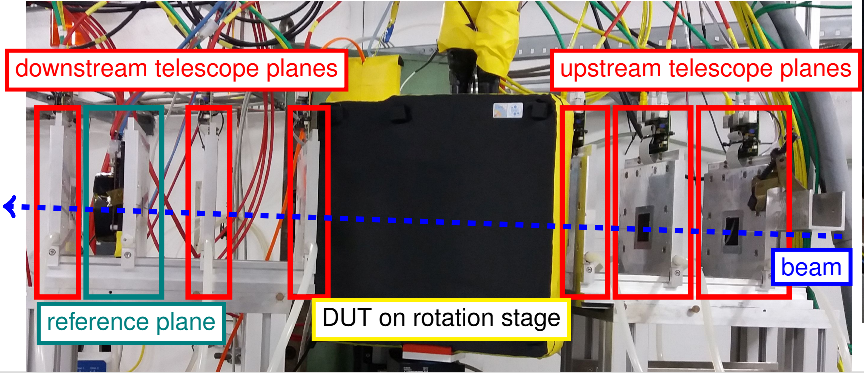


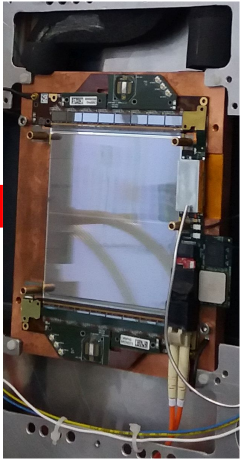


3. Beam Tests with 2S Modules

Beam Tests with 2S Modules – Setup

- Expose modules to high energetic particle beam (e.g. 5 GeV e^-)
- Telescope for particle tracking
  → µm precise track prediction on device under test (DUT)
- Compare hits on module with track to define detection efficiencies

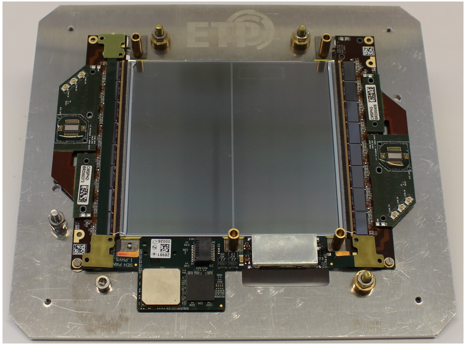


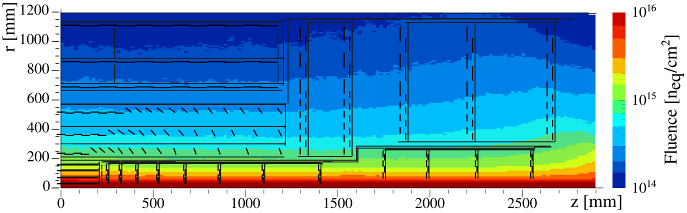


Beam Tests with 2S Modules – Campaigns

- Three 2S module beam test campaigns in 2019 and 2020 with different sensor configurations
  - Modules with unirradiated sensors
  - Module with sensors irradiated to fluence expected for $3000\,\mathrm{fb}^{-1}$ to $4000\,\mathrm{fb}^{-1}$: $4.6 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$

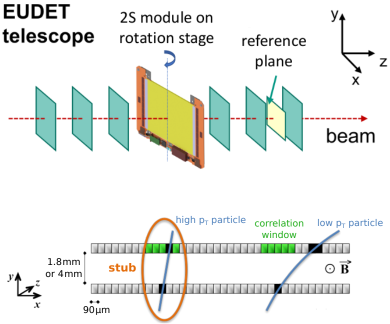
⇒ **Probing of module efficiency at start and end of lifetime of CMS detector possible**

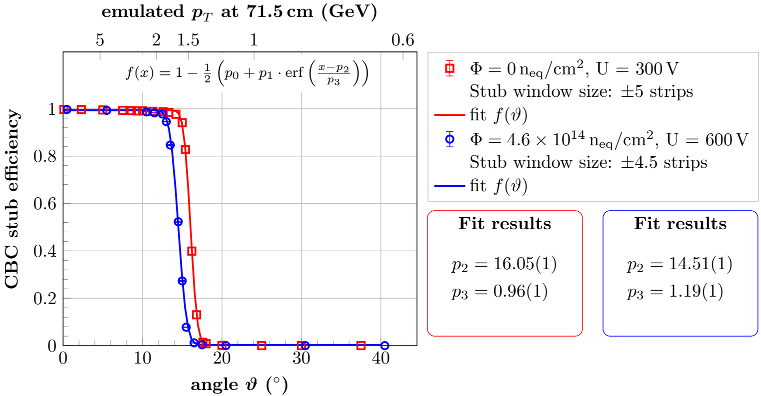




Beam Tests with 2S Modules – Angular Scan

- Turn module with respect to beam to emulate bent particle trajectories
- Plateau at 100% efficiency within correlation window
- Sharp drop to zero outside of correlation window at expected rotation angles
- Larger stub window size results in lower p_T cut





Summary

- High Luminosity LHC leads to increased challenges for accelerator and detector components
- ETP contributes to development of new CMS Outer Tracker
  - Assembly and Testing of 2S module prototypes using custom designed fixtures
- Module functional tests in dedicated test setup for comparable results
- Module resilience tests yield excellent results after extensive thermal stress
- Silicon sensors show efficient operation at the end of HL-LHC runtime in prototype modules

Outlook:

- 2S Module (pre-)production will start in 2023
- Until then: finalisation of module design, assembly fixtures and test stands
- End of 2S Module production in June 2025

Backup